Title
LSST Observing Strategy White Paper: LSST Observations of WFIRST Deep Fields

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LSST Observations of *WFIRST* Deep Fields

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Abstract

The Wide-Field Infrared Survey Telescope (*WFIRST*) is expected to launch in the mid-2020s. With its wide-field near-infrared (NIR) camera, it will survey the sky to unprecedented detail. As part of normal operations and as the result of multiple expected dedicated surveys, *WFIRST* will produce several relatively wide-field (tens of square degrees) deep (limiting magnitude of 28 or fainter) fields. In particular, a planned supernova survey is expected to image 3 deep fields in the LSST footprint roughly every 5 days over 2 years. Stacking all data, this survey will produce, over all *WFIRST* supernova fields in the LSST footprint, ∼12–25 deg^2 and ∼5–15 deg^2 regions to depths of ∼28 mag and ∼29 mag, respectively. We suggest LSST undertake mini-surveys that will match the *WFIRST* cadence and simultaneously observe the supernova survey fields during the 2-year *WFIRST* supernova survey, achieving a stacked depth similar to that of the *WFIRST* data. We also suggest additional observations of these same regions throughout the LSST survey to get deep images earlier, have long-term monitoring in the fields, and produce deeper images overall. These fields will provide a legacy for cosmology, extragalactic, and transient/variable science.

1 White Paper Information

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1. **Science Category:** Our proposed observations would directly address the "constraining dark energy and dark matter" and "exploring the transient optical sky" science goals outlined in the LSST SRD. The observations would also significantly improve extragalactic science and improve calibration efforts for both LSST and *WFIRST*.

2. **Survey Type Category:** Our proposal falls under the category of mini survey since the observations do not need to be performed for the entire 10-year LSST survey. However, during the 2-year period, the observations are similar to the deep-drilling field observations.

3. **Observing Strategy Category:** We request an integrated strategy to observe the specific *WFIRST* supernova deep fields during the 2-year *WFIRST* supernova survey. Ideally, the cadence and timing of the observations would be matched to that of *WFIRST*. We would prefer observations in all LSST filters to deep-drilling field depths. A combined *WFIRST*–LSST supernova survey strategy also satisfies the science requirements for a wide variety of other scientific applications that can be studied with deep extragalactic fields.

2 Scientific Motivation

WFIRST is the top space-based priority from the 2010 Decadal survey and will be the flagship NASA mission following the James Webb Space Telescope (*JWST*). *WFIRST* has a 2.4-m mirror and a highly capable instrument suite (for a detailed description, see Spergel et al., 2015). For the purposes of this white paper, we focus on the Wide-Field Instrument (WFI), a 0.28-deg^2 imager with a complement of several wide filters ($RZYJHF$, and one ultra-wide) and a grism. It will have an angular resolution comparable to the *Hubble Space Telescope*, but with a field of view that is ∼100 times larger.

Following the recommendations of the 2010 Decadal survey, the *WFIRST* Project is preparing for several surveys to address science topics related to exoplanets and dark energy. In particular, we expect a relatively shallow High-Latitude Survey (HLS) covering ∼2000 deg^2 overlapping the LSST footprint and a Supernova (SN) survey that will repeatedly visit ∼40 deg^2.

The *WFIRST* SN survey (see Hounsell et al., 2018) is expected to have a cadence of ∼5 days over a period of 2 years (the middle 2 years of the 5-year mission). It is expected to observe 20–40 deg^2 to ∼22 mag in single epochs (the "shallow" fields) and 5–15 deg^2 to ∼25–26 mag in single epochs (the "deep" fields). The shallow and deep fields will likely be observed in $RZYJ$ (and possibly H) and $YJHF$ (and possibly Z), respectively. Stacking all exposures over the 2-year survey, we expect the shallow and deep fields to reach depths of ∼28 and 29 mag in each filter, respectively.

With these data, we will discover ∼20,000 Type Ia supernovae (SNe Ia). With the SN light-curve data, we will constrain the expansion history of the Universe to $z \approx 3$. We will detect ∼8000 SNe Ia at $z < 1$, for which LSST can obtain complementary $ugrizy$ light curves, resulting in data from 0.3–2 μm. The combined optical/NIR light curves will (1) improve the distance precision of these SNe beyond what either telescope could do alone, (2) provide strong systematic tests by tracking the rest-frame optical from $z = 0$ to $z = 3$, (3) increase the wavelength coverage, constraining dust properties, and (4) provide end-to-end testing of transient object detection and characterization at the faintest magnitudes LSST probes. Using the *WFIRST* prism, we will obtain redshifts and classifications for a subset of these SNe.

Additionally, these fields will be used to calibrate photometric redshifts (photo-z's), critical for several science cases for LSST and *WFIRST*. To maximize the utility of these data, having similar depths in both LSST and *WFIRST* filters is required (Hemmati et al., 2018). The additional *WFIRST* photometry and high-resolution images will break photo-z degeneracies and improve the precision for all galaxies. With the high-resolution imaging, one can better deblend galaxies and construct empirical models how blends affect photo-z's. Finally, the deeper imaging will result in significantly higher signal-to-noise measurements for galaxies of a given luminosity than the combination of HLS and the WFD surveys.

Deep spectroscopic observations are needed to calibrate the *WFIRST* HLS grism survey. To obtain 1% redshift purity at the *WFIRST* HLS flux limit, 22 $\deg^2$ of deep grism spectroscopy are planned with at least 10 observation sets. Each set, which is designed to duplicate the main HLS grism survey observations, is obtained at 4 different roll angles, resulting in a total of $\geq$40 separate spectral observations (each at a different roll angle) of these fields. We expect these calibration fields to coincide with the SN fields that overlap with the HLS. We expect these observations will yield a 99.9% completeness with negligible confusion. The HLS grism survey calibration observations will provide spectroscopic redshifts for SN host galaxies, and enable the calibration of photometric redshifts for weak lensing observations for both *WFIRST* and LSST.

The *WFIRST* deep fields will establish a unique and important legacy for extragalactic science, covering a range of scientific questions from reionization through the peak epoch of star formation. Coordinated *WFIRST*–LSST deep fields would provide exquisite imaging in $\sim$10 filters to sufficient depth and area to tackle an enormous range of scientific questions from reionization through the peak epoch of star formation. The statistical returns for the galaxy populations yielded by such a survey are transformational. In the deep fields, where deep LSST imaging will be critical for photo-z vetoes, we will discover $\sim 10^5$ $z \approx 8$ galaxies. These objects will be selected over an area and depth that will uniquely complement redshifted 21-cm observations of the IGM neutral fraction, allowing for cross-correlations between galaxies and the IGM ionization state that will crystallize our understanding of how reionization unfolded. We will obtain rest-frame optical observations for $z \lesssim 3$, providing precise stellar masses that can be compared to their rest-frame UV derived star-formation rates. We will simultaneously constrain the abundance of the most massive galaxies at $z > 4$, which will provide constraints on the efficiency of star formation at these epochs, and will allow us to quantify the demographics of the first galaxies to cease their star formation, yielding insights into the physical mechanisms responsible for quenching.

Combining the LSST photometry with *WFIRST* grism spectra will enable Hα+[O III] observations for $\sim 10^6$ galaxies at $z \approx 2$, enabling a cross correlation between star-formation rate, rest-frame UV emission, high-resolution rest-frame optical morphology, and cosmic environment/spatial clustering. The abundance of relatively low-luminosity active galactic nuclei and their connection to their host galaxies can be measured for samples of unprecedented size at $z > 4$. Further combining with the weak-lensing-based estimates of dark matter halo mass, these data will provide definitive measures of the relationship between galaxy and dark matter halo properties and the connection between star formation, stellar mass, and halo growth, leading to invaluable constraints on theoretical models of galaxy formation. The *WFIRST*–LSST collaborative survey efforts therefore have the potential to rewrite the origin story of modern galaxies.

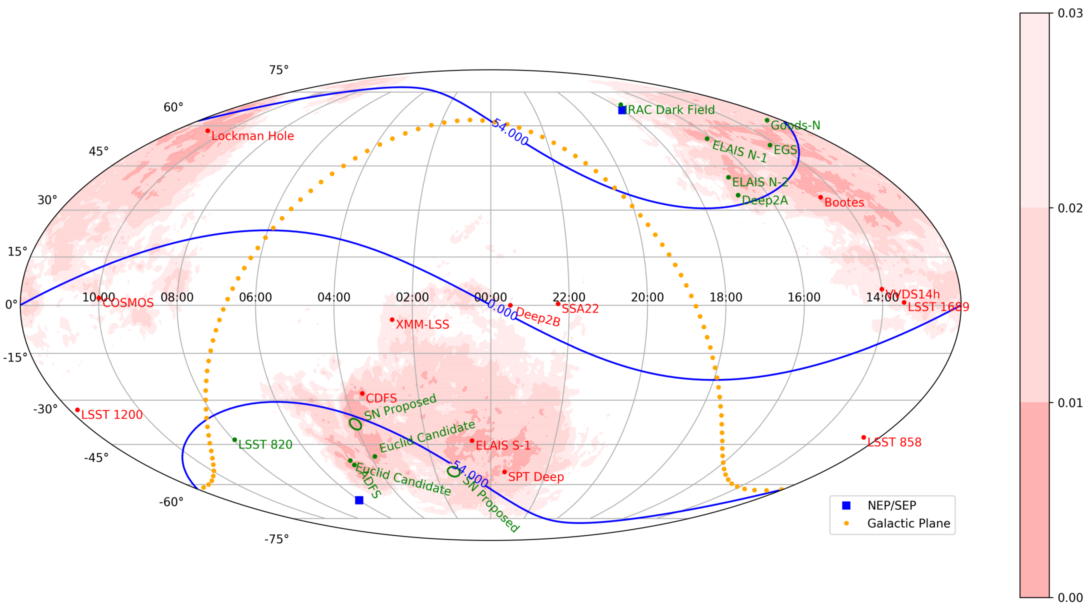

Figure 1: Equatorial map of the sky indicating potential SN fields for *WFIRST* and LSST. The red shading displays the Milky Way reddening (as indicated by the color bar on the right) with lower reddening values being darker. The Galactic plane is represented by the gold dots. The ecliptic plane is indicated by the central blue line (labeled 0.000) and the ecliptic poles are marked with blue squares. Ecliptic latitudes of $|54°|$, corresponding to the edge of the *WFIRST* continuous viewing zone (CVZ) are also displayed as blue lines. Several extragalactic fields are marked with those in green being in the *WFIRST* CVZ. The three proposed *WFIRST* SN deep fields overlapping the LSST footprint are the AKARI Deep Field South (labeled "ADFS"), which will also be observed by Euclid, and those labeled "SN Proposed."

3 Technical Description

3.1 High-level description

We request "simultaneous" observations of all *WFIRST* SN fields in the LSST footprint. The *WFIRST* observing sequence is currently designed to take 30 hours every 5 days, making truly simultaneous observations impossible for all fields. However, it is likely that the different fields can be somewhat staggered, allowing planned LSST observations to be within 12 hours of *WFIRST* observations.

We request a sequence of "deep-drilling"-type depth exposures for each visit, reaching $u \approx 23.5$, $g \approx 25.3$, $r \approx 25.6$, $i \approx 25.4$, $z \approx 24.9$, and $y \approx 24.0$ mag (depending on the lunar phase). All filters could be observed in a single visit, but observing all filters over a few nights would be acceptable as long as at least two filters (one color) is observed each night of observations. The stacked depth of these fields would be slightly shallower than the final stacked depths of deep drilling fields ($ugrizy = 26.8$, 28.4, 28.5, 28.3, 28.0, 26.2 mag, respectively).

Since *WFIRST* will obtain deep observations in ZY, LSST zy observations are not critical for all science presented above. However, some science cases such as LSST photo-z training may require significantly deeper images than the WFD zy observations will produce.

The *WFIRST* SN survey is expected to occur in the middle 2 years of the mission. If *WFIRST* is launched in early 2025, the SN survey should occur roughly from 2027–2028. Our fields (see below) will not be observable with LSST during this entire period. Nonetheless, we request observations whenever feasible, including possibly reducing the number of filters observed to increase the time baseline (or possibly observing different filters over several consecutive nights).

To prepare for the *WFIRST* SN survey, for HLS calibration, and as a jump-start on extragalactic science enabled by the SN survey observations, we expect *WFIRST* will obtain relatively deep imaging of the SN fields during commissioning or early in science observations. We also expect occasional visits to these fields as part of normal survey operations, to monitor variable sources, and as calibration touchstone fields. We therefore request regular monitoring of the fields, at least twice a year at deep-drilling depths for all years when the *WFIRST* SN survey is not running.

Given the current level of uncertainty for *WFIRST* launch and performance, the plan for observing its deep fields should be reconsidered as the *WFIRST* plans develop.

The *WFIRST* Project will work to define fields to best fit within the circular LSST field of view (if *WFIRST* SN fields are <10 deg^2) or multiples of the LSST field of view (if *WFIRST* SN fields are >10 deg^2).

3.2 Footprint – pointings, regions and/or constraints

The *WFIRST* SN fields must be located in the continuous viewing zone (CVZ) to avoid significant gaps and edge effects in supernova light curves. The current field of regard is 54°, constraining the CVZ to declinations of $\delta > |30|$ (the exact constraints are shown in Figure 1). No currently selected deep-drilling field is in the *WFIRST* CVZ. Additional constraints are low Milky Way reddening, low zodiacal light (which is a non-factor in the CVZ), and avoiding bright stars. These constraints limit the possible overlap with LSST to roughly R.A. between 22 and 6 hours and declinations between −30 and −75.

While the exact *WFIRST* SN field sizes and field centers have not yet been determined, we have selected 4 rough positions, 3 of which are in the LSST footprint. These fields are at (approximately) (α, δ) = (01:00, -55:00), (04:00, −35:00), and (04:44, −53:20), with the last field coinciding with the AKARI Deep Field South (Clements, 2012). Notably, Euclid has decided to make the AKARI Deep Field South one of their deep fields, thus obtaining deep, high-resolution *RIZ* imaging to 27.2 mag, spectral data with their 0.9–1.2 μm grism, and long-term (although shallow) light curves in *YJH*.

In addition to the above criteria, these regions have significant advantages over other fields. In particular, they are roughly as far separated as possible within the acceptable southern CVZ, reducing cosmic variance concerns, allowing for isotropy tests, and improving observability from ground-based telescopes.

If the *WFIRST* field of regard improves by ∼5°, the Chandra Deep Field South (CDF-S) will be in the CVZ. Being an existing deep-drilling field and Euclid deep field, having extensive existing multi-wavelength data, and being accessible to Northern-hemisphere telescopes, it is superior to the choices for *WFIRST* SN fields listed above. In the case that the field of regard improves sufficiently, we will likely move the (04:00, −35:00) field to CDF-S. Similarly, if the field of regard increases slightly beyond that, we may shift the (01:00, −55:00) field to the existing deep-drilling field centered on the ELAIS deep field.

While the fields have not been precisely defined now, the field of regard will be better defined once the Project enters Phase C (within roughly 1 year). Furthermore, the *WFIRST* SN survey will occur 2 years into the mission, providing sufficient time to determine the in-orbit field of regard before LSST observations are required. We encourage LSST to continually contact the *WFIRST* Project for updates.

3.3 Image quality

We have no constraints on image quality. Cadence is more important.

3.4 Individual image depth and/or sky brightness

We request observations that follow the deep-drilling strategy, reaching $u \approx 23.5$, $g \approx 25.3$, $r \approx 25.6$, $i \approx 25.4$, $z \approx 24.9$, and $y \approx 24.0$ mag (depending on the lunar phase).

3.5 Co-added image depth and/or total number of visits

We request a cadence matched to the *WFIRST* cadence while the fields are available and during the SN survey. We also request 2 observations per year for the years when the SN survey is not active.

The stacked depth of these fields would be slightly shallower than the final stacked depths of deep drilling fields ($ugrizy$ = 26.8, 28.4, 28.5, 28.3, 28.0, 26.2 mag, respectively). These depths are comparable to the "shallow" *WFIRST* SN fields (reaching $\sim$28 mag).

3.6 Number of visits within a night

We do not require more than 1 visit per night.

3.7 Distribution of visits over time

We request a cadence that matches the *WFIRST* SN survey (currently planned to be 5 days, but initial attempts to optimize suggest perhaps a 7-day cadence being optimal). The observations should occur during the *WFIRST* SN survey.

We currently make no recommendations for weather loss. The *WFIRST* light curves should be sufficient to constrain the time of peak brightness for SNe. However, if one wants to use the LSST data independently from *WFIRST*, additional observations surrounding (expected) bad weather may be desired.

All filters could be observed in a single visit, but observing all filters over a few nights would be acceptable as long as at least two filters (one color) is observed each night of observations.

3.8 Filter choice

We request observations in $ugrizy$. However, $ugri$ are particularly unique and most important.

3.9 Exposure constraints

We request deep-drilling style observations.

3.10 Estimated time requirement

Scaling from estimates for the deep-drilling fields, but with our cadence and season duration, we expect each field to require 158 hours, for a total of 474 hours (roughly 1.5% of total survey time), if full *ugrizy* observations are performed. If observations are restricted to *ugri*, each field would require 95 hours with a total of 286 hours (roughly 0.9% of total survey time) for all fields.

Properties	Importance
Image quality	3
Sky brightness	2
Individual image depth	1
Co-added image depth	2
Number of exposures in a visit	2
Number of visits (in a night)	3
Total number of visits	1
Time between visits (in a night)	3
Time between visits (between nights)	1
Long-term gaps between visits	1
Other (please add other constraints as needed)	

Table 1: **Constraint Rankings:** These rankings primarily reflect our desire to have simultaneous observations with the *WFIRST* SN survey. Cadence/ season duration (and thus number of total visits and gaps between visits) along with individual exposure depth are most important.

3.11 Technical trades

1. For most science, we must reach a depth similar to the *WFIRST* observations (both single exposures and stacked depth) to maximize science. Shallower images will result in a smaller redshift range with overlapping SN and galaxy observations. Reducing area directly affects the number of objects with data from both telescopes, but is independent of redshift/luminosity. Reducing observing seasons will reduce the overall stacked depth and produce more extreme "edge effects" for the SNe where SN light curves will be cut off. Because of time dilation, this has an outsized effect on higher-z SNe.

2. Trading fewer visits for deeper exposures will likely result in insufficient light-curve coverage (especially if weather losses are not mitigated). Trading individual-

exposure depth for additional visits will result in a smaller redshift range (see above) and have an unnecessarily high cadence.

3. Adjusting the individual exposure times to reach a predetermined depth could be useful as long as the typical depth is not significantly shallower than a constant exposure-time strategy (i.e., the modes are the same).

4. We could potentially adjust the deep-drilling strategy to spread a set of observations out over a few days to minimize filter changes. However, this would reduce our ability to have simultaneous colors.

4 Performance Evaluation

Primary metrics:

- Total overlapping area with *WFIRST* SN deep fields.
- Number of deep-drilling depth observations of the fields obtained during the *WFIRST* SN survey.
- Number of deep-drilling depth observations of the fields obtained outside the time of the *WFIRST* SN survey.
- Median cadence during the *WFIRST* SN survey.
- Maximum gap between epochs during and outside the *WFIRST* SN survey.
- Total stacked depth in each filter.

Secondary metrics:

- Number of SNe Ia detected by LSST in *WFIRST* SN deep fields during the *WFIRST* SN survey.
- Number of $0.45 < z < 0.55$ SNe Ia with light curves that result in distance modulus statistical uncertainty of 0.05 mag.
- Number of $0.95 < z < 1.05$ SNe Ia with light curves that result in distance modulus uncertainty of 0.05 mag.
- Number density of 5-σ-detected galaxies at a flux level of 10^{-16} erg s^{-1} cm^{-2}.

5 Special Data Processing

We require nightly co-adds of the LSST data and difference imaging of these co-adds. While not required as the data are obtained, combined processing of LSST and *WFIRST* data will be required for some science cases. To provide the most science and reach the largest number of researchers, we suggest having access to the *WFIRST* and LSST data as well as the *WFIRST* and LSST data processing software in a common interactive software environment.

References

Clements, D. L. 2012, Publication of Korean Astronomical Society, 27, 135, doi: 10.5303/PKAS.2012.27.4.135

Hemmati, S., Capak, P., Masters, D., et al. 2018, ArXiv e-prints. https://arxiv.org/abs/1808.10458

Hounsell, R., Scolnic, D., Foley, R. J., et al. 2018, ApJ, 867, 23, doi: 10.3847/1538-4357/aac08b

Spergel, D., Gehrels, N., Baltay, C., et al. 2015, ArXiv e-prints. https://arxiv.org/abs/1503.03757